PB-217 665

# LOW-LEVEL LIQUID SCINTILLATION COUNTING OF ALPHA- AND BETA-EMITTING NUCLIDES

A. A. Moghissi

Southeastern Radiological Health Laboratory
Montgomery, Alabama

1970

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PB 217 665

Reprinted from
The Current Status of LIQUID SCINTILLATION COUNTING
Edwin D. Bransome, Jr., M.D., Editor
Copyright 1970, Grune & Stratton, Inc., New York

# Low-Level Liquid Scintillation Counting of α- and β-Emitting Nuclides

A. A. MOGHISSI

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

10

# 7/Low-level liquid scintillation counting of $\alpha$- and $\beta$-emitting nuclides

A. A. Moghissi

Even in the early days of liquid scintillation counting, potential for low-level counting was recognized. Because of difficulties associated with low-level counting of tritium by other techniques such as internal gas counting, the first efforts reported were in ($^3$H) counting.[1-4]

This chapter reviews the efforts of the Southeastern Radiological Health Laboratory in low-level counting by liquid scintillation. We have dealt primarily with ($^3$H) counting but have recognized that low-level counting of other radionuclides may be carried out advantageously by the same technique. Details of the procedures for each radionuclide discussed are in the process of preparation for publication or have been published.[5,6] All investigations reported here have been carried out using a Beckman liquid scintillation system except where specifically mentioned.

There are a number of factors affecting the performance of low-level counting systems, and various attempts have been made to correlate these factors in a single formula. The major factors determining the sensitivity of a low-level counting system are background, efficiency, and sample size. Other factors, such as the requirements of time and skill for sample preparation, and the convenience of operation, are important but have relatively little effect on the sensitivity of the system.

## Background

In older liquid scintillation counters, the thermal electron emission of photomultiplier tubes (PMT) was the major source of back-

*Mention of commercial products used in connection with work reported in this article does not constitute endorsement by the Public Health Service.*

A. Alan Moghissi, Ph.D.: *Southeastern Radiological Health Laboratory, Department of Health, Education and Welfare, U.S. Public Health Service, Montgomery, Ala. Present address: Southwestern Radiological Health Laboratory, Las Vegas, Nev.*

ground. The development of bialkali PMT's with "noise" levels of 2000–15000 cpm and the application of nanosecond coincidence and circuitry has reduced the contribution of the electronic system to the background to less than 1 cpm. (See Chapter 4.)

As registered in a modern liquid scintillation counter, background is generally caused by external radiation. Cosmic rays and radiation from radionuclides in shielding and other construction materials are the major components of this external radiation. In areas with high air radon concentration, decay products may plate out on surfaces and contribute to background.

In a background spectrum over the range of approximately 2–2000 keV, there is an undesirable peak close to the tritium spectrum, presumably caused by the bremsstrahlung of the cosmic radiation in the shield. Above approximately 50 keV, the background count/channel in a multichannel analyzer seems to be relatively constant. Efforts are under way in our laboratory to reduce the background for ($^3$H), primarily by changing the geometry of the shielding. It is unfortunate that manufacturers of liquid scintillation counters do not offer instruments with an anticoincidence shield. We estimate that such a shield, which would reduce the background to one-third or less of the original value, would increase the price of the instrument by only 10–15 per cent. This increase, well worth the cost, would substantially improve the sensitivity of liquid scintillation counting and, as it may be noted from the following description, make it competitive with other low-level counting systems for high-energy $\beta$- and $\alpha$- emitters.

While the contribution of external radiation to the background is relatively constant, there are other additional factors responsible for the lack of precision of background observed by many investigators. The variety of reactions that may produce light in the scintillation liquid—phosphorescence, chemiluminescence, and static electricity—are very important.

*Phosphorescence*

In our laboratory a great deal of work has been carried out dealing with phosphorescence and its temperature dependence. Three mixtures were given special attention: a dioxane-water solution with a volume ratio of 80:20 (DW),[5] a *p*-xylene, Triton N-101 and water emulsion with a volume ratio of 44:16:40 (XTN),[7] and a toluene, Triton X-100, water emulsion with a ratio of 55:25:20 (TTX).[8] The concentration of scintillators was in all cases 7 g diphenyloxazole (PPO) and 1.5 g p-bis(o-methylstyryl)-benzene (bis-MSB) dissolved in one liter of organic solvent. The dioxane contained 120 g naphthalene/l.

The excitation by light of detergent mixtures (XTN and TTX) was 10 times stronger than with dioxane (DW) solution. In all three cases there were three decay components: short (half-life $< 0.5$ minute), intermediate, and long (half-life 4–6 hours).

The intermediate component had a half-life of 30 minutes for DW, 20–25 minutes for XTN, and 4–6 minutes for TTX. It was found that the emission intensity was reduced by a factor of approximately 2 for DW and 3 for XTN and TTX during the 115-minute interval between 5 and 120 minutes after excitation. The emission intensity of DW was 10 times higher than the other two 5 minutes after excitation. Only the half-life of the intermediate component was subject to reduction by changing the temperature and could be reduced (e.g., by a factor of 2 for DW) by reducing the temperature to less than 16°C. Heating the excited scintillation mixture reduced the phosphorescence substantially, almost to zero, a finding analogous to the thermoluminescence observed in many inorganic scintillators.

Coincidence measurements show that phosphorescence decay is primarily monophotonic. When excitation is intense, random coincidence may occur and pulses in higher energy ranges may be registered. The complexity of phosphorescence suggests the ad-

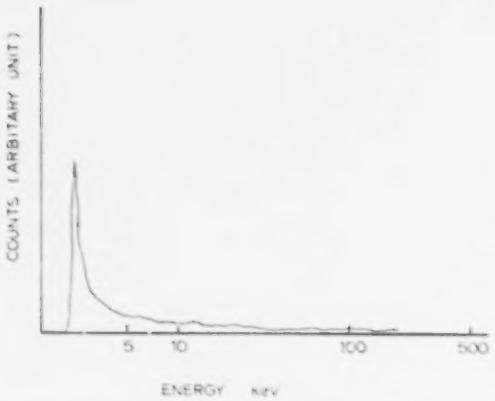


**Fig. 1.**—Spectrum of static electricity in background sample. Indicated energies are approximate and were estimated using ($^{90}$Sr)-($^{90}$Y) and ($^{3}$H).

visability of avoiding it whenever possible. For this reason it has become routine in our laboratory to perform all operations involving scintillation solutions under red light.

*Chemiluminescence*

The production of light as a result of chemical reaction is more complicated than phosphorescence. (See Chapters 32 to 34.) In dioxane-based solutions, impurities, particularly peroxides, cause chemiluminescence. However, high purity dioxane is available and is used along with high-purity scintillators exclusively, in our laboratory. Because of the solubility limitations of DW solution, it is used only for ($^{3}$H) counting.

In suspension systems, the detergent and carrier can also be selected to minimize chemiluminescence. An advantage of this system is the separation of aqueous and organic phases, and although the surface of the interphase is large and each phase is to some extent soluble in the other, the possibility of a chemical reaction is considerably less than in a true solution. Heating the mixture generally reduces or eliminates chemiluminescence but is inconvenient and not always possible because of chemical reactions that may destroy the scintillators. In some cases, scintillators may be added in concentrated solution to the sample after the latter was heated with a portion of the solvent. In other cases, reducing the temperature may be helpful.[9]

The selection of any low-level counting system should include the consideration of chemiluminescence. As chemiluminescence may be enhanced by light, exposure of the sample to light should be avoided.

*Static Electricity*

As radioactive sources are extensively used in the industry to eliminate static electricity, it is ironic that in a radioactivity counting system, perturbations from static electricity must be considered. As may be seen from Fig. 1, static electricity should always be considered in the background in ($^{3}$H) counting when the sample moves an appreciable distance in the sample-changer compartment. To avoid static electricity, it is advisable to arrange samples within the changer compartment so that none travels more than five places immediately before it is counted.

## Efficiency and Sample Size

The quantum efficiency of PMTs is an essential factor in selecting a low-level counting system for reasons reviewed recently.[8] Bialkali PMTs with approximately 30 per cent quantum efficiency are now available. Counting efficiency $E$ is closely related to the degree of quenching and to the sample size, the amount $M$ of the radionuclide (and its carrier) introduced into the scintillation mixture. For water, it has long been recognized that

the product $E \times M$ is the determining factor in low-level tritium counting. This is also valid for other radionuclides if the optimum amount of the sample is available for analysis, as is often the case for ($^{14}$C) and ($^{45}$Ca). For low-level counting of those radionuclides present in a sample at trace levels, such as ($^{239}$Pu), conditions may often be found for which the efficiency is close to 100 per cent.

## Correlation of Efficiency, Sample Size, and Background

We recently defined a *Y*-value for the comparison of low-level counting systems.[6] This value, (in picocuries) the minimum limit of detection at a 1-$\sigma$ confidence level and a one-minute counting time, correlates background $B$ (cpm), efficiency $E$ (cpm/dpm), and the amount of sample in the scintillation mixture $M$ (g):

$$Y(\text{pCi/g}) = \frac{\sqrt{B}}{2.22 \times E \times M} \qquad (1)$$

If the optimum amount of carrier is not available, Equation (1) is replaced by

$$Y(\text{pCi/sample}) = \frac{\sqrt{B}}{2.22 \times E} \qquad (2)$$

Due to the efficiency dependence of background, 100 per cent efficiency does not necessarily represent the optimum *Y*-value. Experiments with many radionuclides in our laboratory have shown that optimum *Y*-values are usually at efficiencies between 80–90 per cent for radionuclides with a maximum $\beta$-energy of over 200 keV.

### ($^3H$) *Counting*

Low-level counting of ($^3$H) has undergone vast improvements in recent years. There have been three general approaches for incoporating a large amount of water in the scintillation mixture: solution in dioxane-based mixtures,[1-5] conversion to a compound such as benzene,[10] and suspension in aromatic solvents.[7,8,11-13] The lowest *Y*-value obtainable with a dioxane-based mixture is 1.1 pCi/g $H_2O$ using the solution previously abbreviated as DW.[6] In suspension systems the best *Y*-value for Triton X-100 seems to be 1.4, as reported by Williams.[13] The application of a modern liquid scintillation counter with bialkali PMTs could reduce this value to 1.0 pCi/g $H_2O$. The lowest *Y*-value for a Triton N-101 suspension is approximately 0.6 pCi/g $H_2O$ with the composition abbreviated previously as XTN.

Several authors report instabilities associated with suspension counting.[11-13] Refrigerated liquid scintillation counters have been used in all cases where these instabilities are mentioned. The suspension of water in an aromatic solvent is based on the surface tension of the produced water bubble in the organic liquid. Due to temperature dependence of surface tension, a large temperature reduction may change the equilibrium established between the two phases at room temperature and could be the cause for reported instabilities of the suspension system. (See Chapter 19 for temperature optima of suspensions.) Two corrective techniques have been proposed.[11-13] The first consists of repeated shaking of the mixture as it is cooled. During this process, the distorted equilibrium is redistributed at intermediate temperatures until the final temperature is reached. The second technique consists of heating the counting vial for approximately 30 minutes at approximately 40°C. The actual effect of this treatment is not entirely clear, but apparently a stable and irreversible condition can be established which can tolerate a reduction of 20°C without noticeable change in the equilibrium of the system. The suspension system developed in our laboratory can be used between 17 and 25°C. It is stable and reproducible within this temperature range, so that neither treatment is necessary for reproducible results.

Low-level ($^3$H) counting in urine[14] has been made possible by the advances in suspension counting. The major source of uncertainty is the presence of other radionuclides in raw urine, particularly ($^{14}$C) and natural ($^{40}$K).

Activities of 10 nCi/l or more are easily detectable with a Triton N-101:*p*-xylene (7-g PPO and 1.5-g bis-MSB/l) mixture in a volume ratio of 1:2.5. Eight ml of urine and 17 ml of the above mixture result in a *Y*-value of 1.4 pCi/ml ($E = 0.15$, $B = 12$).

The most sensitive technique for low-level counting of ($^3H$) consists of a synthesis of benzene[10] through the reaction of calcium carbide and water followed by a trimerization of the resulting acetylene to benzene. Due to an isotope effect, the specific activity of ($^3H$) in benzene is only 70–80 per cent of that in the water, and the process is time consuming and elaborate. The *Y*-value of this method, if 25 ml of benzene were synthesized, would be 0.3 pCi/g $H_2O$.

### ($^{14}C$) *Counting*

Low-level counting of ($^{14}C$) by liquid scintillation is considerably more complicated than that of ($^3H$). Inasmuch as the conversion of the sample to $CO_2$ is usually the start of the ($^{14}C$) procedure, the introduction of a sufficient amount of $CO_2$ into the scintillation liquid is necessary. Many chemical reactions have been proposed for converting $CO_2$ to a suitable compound. The only reaction with wide acceptance is the conversion of $CO_2$ to a carbide and the trimerization of the latter to benzene.[15] The *Y*-value of this process, if 25 ml benzene were prepared, would be 0.12 pCi/gC ($E = 0.85$, $B = 20$, and $M = 20$ g). This excellent sensitivity depends however, on very elaborate equipment and techniques. The preparation of 25 ml of benzene would require approximately a week, and a rather large sample is needed. For these reasons, benzene synthesis is not feasible for the routine monitoring of ($^{14}C$) in environmental samples.

Another technique has recently been developed in our laboratory. The essential features of our procedure are as follows: the sample is converted to $CO_2$ and is reacted with lithium hydroxide to produce lithium carbonate. Due to large differences in the solubility of LiOH and $Li_2CO_3$ in water-alcohol mixtures, the recovery of $Li_2CO_3$ is large and can be made quantitative by the evaporation of the solvent. The critical portion of this procedure is the removal of entrapped solvent from the $Li_2CO_3$ crystals by drying in a desiccator overnight. A counting vial is then filled with 12.5 g of the $Li_2CO_3$ and 15 ml of an aromatic solvent scintillator. This mixture has been counted with 55 per cent efficiency and a background of 20 cpm, resulting in a *Y*-value of 1.8. The *Y*-value of this method is considerably higher than that of the benzene synthesis, but it is sensitive enough for monitoring environmental ($^{14}C$) and for ($^{14}C$) dating in the large-volume liquid scintillation counter described later in this chapter. An additional method, oxygen combustion, is described in Chapter 23.

### ($^{45}Ca$) *Counting*

The introduction of an inorganic ion into a scintillation mixture may be accomplished by several techniques. (See Chapter 18.) A number of organic compounds have been used to extract ions from aqueous solutions and introduce the organic phase then being introduced into the scintillation liquid. The maximum amount of sample that may be introduced into the scintillation liquid by this technique is usually quite limited. A second technique consists of suspending an insoluble salt in an aromatic solvent. The ($^{14}C$) procedure described above is an example of this technique. If there is not enough sample to fill the entire counting vial, a technique such as the one described by Bollinger et al[16] may be applied. A third approach may be employed if the scintillation mixture contains a large amount of water: a water soluble salt may be used to incorporate adequate amounts of the sample into the scintillation mixture. Depending upon the available sample size, the latter two techniques may both be used for calcium. Calcium fluoride is known to be an excellent light conductor. It is insoluble in water and moderately concentrated acids and bases and

is easy to prepare. Up to 30 g of $CaF_2$ may be added to a conventional counting vial resulting in a *Y*-value of 0.4 pCi/gCa ($E = 0.30$, $B = 20$ cpm).

For determination of ($^{45}$Ca) in samples where less than 15 g calcium are available, an aqueous solution of calcium chloride may be used. *P*-xylene (containing 7 g PPO and 1.5 g bis-MSB/l) is mixed with Triton N-101 in a volume ratio of 2.5:1. Fifteen ml of this solution can incorporate 10 ml of water containing a large amount of inorganic ions. A variation of the added amount of Ca between 0 and 800 mg changes the efficiency from 100 per cent to 85 per cent, yielding a *Y*-value of 3 pCi/g Ca. This technique is well suited for radiobioassay of calcium in urine and feces.

These values compare favorably with those reported by Hardcastle et al.[17] of 20 pCi/g Ca ($E = 0.85$, $M = 150$ mg, and $B = 30$ cpm). The best *Y*-value with their procedure, if the volume of the sample were increased from 15 to 25 ml and if a modern liquid scintillation counter were used, would be approximately 10 pCi/g Ca.

### ($^{55}$*Fe*) *Counting*

Liquid scintillation is particularly suitable for low-level counting of this radionuclide. The major problem in counting iron is the conversion of the ferric-ion to colorless compounds. Cosolito et al.[18] obtained a *Y*-value of 0.33 pCi/mg Fe ($B = 6$ cpm, $M = 20$ mg and $E = 0.17$) by extracting iron with Di-(2-ethylhexyl)-phosphoric acid (EHPA) and the addition of 5 ml of EHPA to 15 ml of a toluene-based scintillation liquid containing 50 g/l of naphthalene. The *Y*-value of this technique in a modern liquid scintillation counter would be approximately 0.2 pCi/mg Fe.

Iron fluoride is colorless and has considerable solubility in water. If iron hydroxide is dissolved in a limited amount of HF, the resulting solution may be introduced in a suspension as described for ($^{45}$Ca). The only critical point in this procedure is the need for careful control of the amount of HF. The counting efficiency is changed only slightly by the addition of 0–250 mg of iron. The *Y*-value of this system is 55 pCi/g Fe ($E = 0.1$, $M = 0.25$ g and $B = 9$ cpm). This technique is well suited for low-level counting of iron in environmental samples.

### ($^{85}$*Kr*) *Counting*

Low-level counting of krypton by liquid scintillation is based on the solubility of krypton in aromatic solvents. Curtis et al.[19] report a simple liquid scintillation technique which, however, suffers from lack of reproducibility due to partial evaporation of krypton from the liquid phase. Sax et al.[20] report a plastic scintillation technique with a *Y*-value of 2 pCi/ml Kr ($B = 25$, $M = 1.2$ ml, and $E = 0.95$). A newly developed procedure in our laboratory for determination of ($^{85}$Kr) is accurate, sensitive and reproducible.

An evacuated glass vial (25 ml) with a luer fitting is connected to a krypton container and filled with krypton to a pressure of approximately 500–600 mm mercury. The vial, which is closed with a luer stopcock, is removed and connected to a 50-ml syringe filled with an aromatic-based scintillator. If this solution is deaerated, krypton is easily soluble in the aromatic solvent and the vial can be filled to the top with liquid within a few minutes. The stopcock is then removed and the vial sealed with a luer stopper. No krypton loss has been observed if the vial is left open for several minutes. Removal of the stopcock does not endanger the results even if it is carried out slowly. The counting efficiency of a sealed vial does not change over several months. The *Y*-value of this system is 0.14 pCi/ml Kr ($E = 0.9$, $B = 22$, and $M = 17$–$20$ ml).

### ($^{87}$*Rb*) *Counting*: *Determination of Natural Rubidium*

Although for determining natural rubidium there are more sensitive techniques such as atomic absorption spectroscopy, the ease of operation of liquid scintillation offers some

advantages for determination of rubidium in environmental samples. Rubidium is easily separated by ion exchangers of the metal hexacyanoferrate-II type. The limitations of determinating rubidium are given by the long half-life ($4.7 \times 10^{10}$) which results in a very low rate of isotopic decay and the abundance of ($^{87}$Rb), 27.8%, resulting in only 29 dpm/mg of natural rubidium. The efficiency of rubidium in a mixture described for ($^{45}$Ca) is close to 100 per cent, but the optimum efficiency is 90 per cent for a background of 16 dpm. The *Y*-value is consequently 2 pCi/sample.

### ($^{147}$*Pm*) *Counting*

The abundance of this radionuclide in the fission process and, consequently, its relatively low price, have led to a number of new applications for promethium; e.g., for production of self-luminous compounds. Determination of the radionuclide in environmental samples and radiobioassay of dial painters are two areas where liquid scintillation counting may be advantageously used.

Praseodymium (10 mg) is used in our laboratory as carrier for determination of radiochemical recovery of promethium. After anion exchange separation, the two possible interfering elements (Ce and Eu) are separated by their differences in valency from promethium if their presence is suspected. The radiochemical recovery is determined by weighing praseodymium oxalate that is subsequently dissolved in an EDTA solution. The final scintillation mixture is identical to the one described for ($^{45}$Ca). With an efficiency of 85 per cent and a background of 12 cpm, the *Y*-value corresponds to 1.8 pCi/sample.

### *Counting* ($^{90}$*Sr*), ($^{89}$*Sr*) *and* ($^{90}$*Y*)

Low-level counting of these radionuclides is similar to that described for ($^{147}$Pm). Inasmuch as strontium oxalate is insoluble in EDTA, the carbonate that can be dissolved in a few drops of hydrochloric acid is used instead. The *Y*-value for these radionuclides is approximately 2 pCi/sample.

($^{89}$Sr) is usually accompanied by ($^{90}$Sr). In a conventional liquid scintillation counter, 10–20 per cent of ($^{89}$Sr) counts are registered in the ($^{90}$Sr) channel if the latter is set for an efficiency of 80 per cent. This is inadequate for environmental ($^{89}$Sr)-($^{90}$Sr) analysis. However, it permits an estimation of ($^{90}$Sr) level in the presence of ($^{89}$Sr) while a quantitative assessment is easily made by a recount of the sample after two weeks. The ingrowth of ($^{90}$Y) corresponds to the ($^{90}$Sr) level of the sample.

### ($^{36}$*Cl*) *Counting*

The only sensitive low-level counting technique previously reported for chlorine is that of Ronzani and Tamers.[21] They converted chlorine to $SiCl_4$ which can be added up to 55 per cent by volume to a scintillation liquid with a resulting *Y*-value of 0.4 pCi/g Cl. This value may be reduced to 0.25 pCi/g Cl by optimization of the procedure and application of a modern liquid scintillation counter. Although their technique is sensitive, the labor requirements are high, and we have sought other alternatives.

Using a technique similar to that described for ($^{14}$C), the ideal chlorine salt for introduction into a liquid, is lithium chloride. The preparation of LiCl presented severe difficulties, and sodium chloride was consequently used. The difference in solubility of NaOH and NaCl in alcohol made the preparation rapid and easy. Eleven grams of sodium chloride may be introduced in a vial and counted with 95 per cent efficiency. The *Y*-value under optimum conditions is 0.43 pCi/g Cl ($E = 0.85$, $M = 6.6$ g, and $B = 20$ cpm).

### *Counting Plutonium Isotopes*

Numerous low-level counting techniques involving liquid scintillation have been proposed for plutonium. The sensitivity of these is inferior to other techniques such as solid state counting, primarily because of the rela-

tively high background levels encountered in liquid scintillation, but the ease of operation, particularly in sample preparation, has made liquid scintillation popular for plutonium counting. The efficiencies for the four major isotopes: ($^{239}$Pu), ($^{236}$Pu), ($^{238}$Pu) and ($^{241}$Pu), are essentially close to 100 per cent as described, for example, by Lindenbaum et al.[22]

We have obtained similar results using a suspension similar to that described for ($^{45}$Ca). A large amount of inorganic solids can be tolerated, limited by their solubility. Our suspension system is less subject to quenching than the system described by Lindenbaum. The *Y*-value of either system is 2.4 pCi/sample ($E = 0.95$ and $B = 25$ cpm).

### Other Radionuclides

Many other $\alpha$- and $\beta$-emitters have been counted successfully by liquid scintillation in our laboratory and elsewhere. The principle of the techniques are essentially as described for those radionuclides discussed in this paper. For radionuclides with a maximum $\beta$-energy emission of 200 keV or more, counting efficiency is usually 100 per cent and the optimum *Y*-value depends on the proper correlation of efficiency and background. The suspension described for ($^{45}$Ca) is applicable to the low-level counting of the majority of radionuclides. Gaseous radionuclides may be counted in a system similar to that described for ($^{85}$Kr).

### Alpha Spectroscopy by Liquid Scintillation

Horrocks has proposed an ingenious technique for alpha spectroscopy of $\alpha$-emitting radionuclides.[23,24] The carrier-free nuclide is introduced in 250 $\mu$l of a scintillation liquid and counted with one PMT in association with a multichannel analyzer. Although the resolution of this technique is inferior to that of solid state spectroscopy, for example, it is expected to find wide acceptance after proper modifications are made for routine laboratory use.

### A Large-volume Liquid Scintillation Counter

The maximum sample size in a conventional liquid scintillation counter is determined by the capacity (25 ml) of the counting vial. Several large-volume liquid scintillation counters (LVLSC) have been described.[4,25] The optimum conditions of an LVLSC are also governed by the *Y*-value. Our LVLSC consists of a cylindrical Teflon tube with an internal diameter of 5 cm and two Teflon windows. To determine the optimum volume of an LVLSC, tubes of varying lengths are cut and filled with the scintillation mixture. That for ($^{3}$H) is 250–300 ml, with a *Y*-value of 0.25 if the Triton N-101 suspension is used. Recently we have constructed an anticoincidence shield which preliminary experiments show can substantially reduce background. The preliminary ($^{3}$H) *Y*-value of our LVLSC is 0.15 pCi/g $H_2O$. This system may be applied to other radionuclides such as ($^{14}$C) and ($^{36}$Cl). Detailed results of these investigations will be published in the near future.

### Outlook

From the foregoing description it is clear that liquid scintillation is an effective technique for low-level counting of radionuclides. Recent developments have increased the detection capability of this technique considerably. The major drawback of liquid scintillation at present is the contribution of external radiation to the background. It is hoped that instrument manufacturers will attempt to offer anticoincidence shield as an option in the near future. This option would enable those involved in environmental surveillance to use this useful technique for determination of radionuclides such as ($^{90}$Sr).

The development of more sophisticated scintillation mixtures will certainly place more strict requirements on temperature control of liquid scintillation instruments. Temperature dependence of phosphorescence and chemiluminescence is an additional reason for

desirability of temperature control. We feel that it is already desirable to be able to operate our liquid scintillation counters between 10–25°C with an accuracy of ±1°C.

## REFERENCES


1. Furst, M., Kallmann, H., and Brown F. H.: Nucleonics 13: (4) 58, 1955.
2. Werbin, H., Chaikoff, I. L., and Imada, M. R.: Proc. Soc. Exp. Biol. Med. 102: 8, 1959.
3. Butler, F. E.: Anal. Chem. 33: 409, 1961.
4. Kaufman, W. J., Nir, A., Parks, G., and Hours, R. M.: Tritium in the Physical and Biological Sciences, Vol I. Vienna, International Atomic Energy Agency, 1962, p. 249.
5. Moghissi, A. A.: Advances in Chemistry (in press).
6. Moghissi, A. A., Kelley, H. L., Regnier, J. E., and Carter, M. W.: Int. J. Appl. Rad. Isotopes 20: 149, 1969
7. Lieberman, R., and Moghissi, A. A.: Int. J. Appl. Rad. Isotopes (in press).
8. van der Laarse, J. D.: Int. J. Appl. Rad. Isotopes 18: 485, 1967.
9. Kalbhen, D. A.: Int. J. Appl. Rad. Isotopes 18: 655, 1967.
10. Tamers, M., Bibron, R., and Delibris, G.: Tritium in the Physical and Biological Sciences, Vol. I. Vienna, International Atomic Energy Agency, 1962, p. 303.
11. Patterson. M. S., and Greene, R. C.: Anal. Chem. 37: 854, 1965.
12. Benson, R. J.: Anal. Chem. 38: 1353, 1966.
13. Williams, P. H.: Int. J. Appl. Rad. Isotopes 19: 377, 1968.
14. Moghissi, A. A., Lieberman, R., Regnier, J. E., and Carter, N. W.: Health Physics 17: 727, 1969.
15. Tamers, M. A.: Science 132: 668, 1960.
16. Bollinger, J. N., Mallow, W. A., Register, J. W., and Johnson, D. E.: Anal. Chem. 39: 1508, 1967.
17. Hardcastle, J. E., Hannapel, R. J., and Fuller, W. H.: Int. J. Appl. Rad. Isotopes 18: 193, 1967.
18. Cosolito, F. J., Cohen, N., and Petrow, H. C.: Anal. Chem. 40: 213, 1968.
19. Curtis. M. L., Ness, S. L., and Betz, L. I.: Anal. Chem. 38: 636, 1966.
20. Sax, N. I., Denny, J. D., and Reeves, R. R.: Anal. Chem. 40: 1915, 1968.
21. Ronzani, C., and Tamers M. A.: Radiochim. Acta 6: 207, 1966.
22. Lindenbaum, A., and Lund, C. J.: Rad. Research 37: 131, 1969.
23. Horrocks, D. L.: Rev Sci. Instruments 35: 334, 1964.
24. Horrocks, D. L.: Int. J. Appl. Rad. Isotopes 17: 441, 1966.
25. Boyce, I. S., and Cameron, J. F.: Tritium in the Physical and Biological Sciences, Vol. I. Vienna International Atomic Energy Agency, 1962, p. 231.